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Experimental Comparison of Pulse-Amplitude and Spatial Modulations for Vehicle-to-Vehicle Visible Light Communication in Platoon Configurations

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Abstract: Visible light communication (VLC) is an attractive complementary communication technology for vehicular applications such as platooning. Although data rates around 100 kbps are enough for crucial data transmission, it may be useful to reach a few megabits per second for other applications like networking. Such data rates can be reached by using appropriate modulations and clock rates. In this paper, three forms of pulse amplitude modulations (PAM) are compared in a vehicular context: on-off keying (OOK), PAM-4 and generalized space-shift keying (GSSK). A prototype based on off-the-shelf light-emitting diodes (LED) headlamps is used for static tests in straight line configuration, with an inter-vehicle distance up to 30 m, and curves of minimum radius 100 m and inter-vehicle distance of 10 m. These tests show that OOK and GSSK are the most interesting modulations for highway platooning applications. OOK provides indeed a good mobility while remaining simple to implement. A 1 Mbps link of BER below 10^{-6} is thus demonstrated. In GSSK, the data rate reaches 2 Mbps for an equivalent BER. These performances are obtained by using, in particular, two spatially distinct receivers, which limits strongly the complexity of GSSK decoding.

1. Introduction

Platooning has emerged as an interesting solution to limit traffic congestion while reducing fuel consumption. In platooning, a leading vehicle (LV) is followed by one or several following vehicles (FV) able to adjust automatically their trajectory. Vehicle-to-vehicle (V2V) communication is a vital function to ensure a reliable trajectory control, implemented in most of the platooning projects carried out so far by IEEE 802.11p-based technologies [1–3]. Although they support long range and high data rate transmissions, these radio technologies are very sensitive to interferences. This issue is managed by adding heavy protocols, which leads eventually to transmission delays incompatible with platooning requirements [4]. According to the United States Department of Transportation (USDOT), this delay must indeed be kept below 20 ms [5]. Complementary data transmission solutions may thus be useful.

In that sense, the joint use of IEEE 802.11p with visible light communication (VLC) has been explored through simulations and proved to be an interesting solution to ensure reliable V2V communication [6, 7]. From a prototyping perspective, VLC has also attracted lots of research efforts, by using either photodiodes (PD) [8–13] or cameras [14, 15] as light receivers. With PD, data rates around 100 kbps have been demonstrated over ranges of tens of meters, even with commercial off-the shelf (COTS) automotive light-emitting diodes (LED) [9–11]. Such data rates are sufficient to meet the USDOT delay requirements [12] and are in full compatibility with the IEEE 802.15.7 standard for VLC, which recommends to use either the on-off keying (OOK) modulation or the variable pulse-position modulation (VPPM) to reach a maximum data rate of respectively 100 kbps and 266.6 kbps [16]. Although most studies use these modulations, some researches have also explored other techniques like quadrature amplitude modulation (QAM) [13], reaching in this case a data rate of 2 Mbps.

Such higher data rates may be useful to provide network access through VLC and can be obtained using two main solutions. On the one hand, the clock rate can simply be increased. However, the bandwidth of white LED is usually limited to a few megahertz, a parameter that can be enlarged by equalization techniques, but at the cost of the available optical power and thus of the achievable range [17]. On the other hand, the data rate can be extended by using different modulations. Here, we choose to investigate the pulse amplitude modulation (PAM), under its OOK and PAM-4 forms. The latter, although studied for an indoor use [18, 19], does not seem to have been investigated yet for vehicular applications, except in [20] where a commercial system is used but not detailed. In addition, since a vehicle has two front lights, an additional modulation layer can be introduced by generalized space shift keying (GSSK), a scheme where one or several LED are active at the same time instant [21]. If two transmitters are used, then GSSK allows to double the data rate compared to OOK while keeping the same bandwidth requirements. As PAM-4, GSSK has been studied experimentally for home applications [22] but not yet for vehicular communication.

In this work, GSSK is tested experimentally with COTS automotive headlamps in indoor straight line and curve configurations and compared with OOK and PAM-4, for a constant clock frequency of 200 kHz. It is shown that in such low ambient light conditions, OOK, GSSK and PAM-4 provide a bit-error rate (BER) below 10^{-6} either in a straight line up to 30 m, or in curves of minimum radius 100 m and are thus suitable for platoons of vehicles. The clock frequency is then increased to observe how it impacts the different modulations. It is found that OOK and GSSK are less sensitive to the limited bandwidth of the different components used in the transmission chain. 2 Mbps data transmission with a BER below 10^{-6} is demonstrated with GSSK in a cruise mode configuration. Therefore, these modulations may be preferred to PAM-4.

Section II details the different modulations considered in this work whereas Section III describes the design of the experimental set-up. Section IV first details the results obtained when testing this system as it operates at 200 kHz, in straight line and curve configurations. Then, it shows the behavior of the modulations when the clock frequency is increased. Finally, general conclusions and future works are given in Section V.

2. Modulation details

2.1. OOK and PAM-4

OOK is the simplest intensity modulation scheme, where a data bit 1 is sent by radiating a power P_t with the transmitter whereas a data bit 0 is sent by turning it off. In the IEEE 802.15.7 standard, OOK is necessarily used with Manchester coding where, as detailed in Table 1, a 0 in turned into the sequence $\{0, P_t\}$ and a 1 into $\{P_t, 0\}$. Manchester coding is employed to limit the number of consecutive 0 or 1 to two, which avoids visible flicker. It allows also to reshape the spectrum of the transmitted signal by moving its main lobe center frequency from zero to $f_c/2$. In outdoor applications, the different ambient light sources generate interferences of frequencies up to a few tens of kilohertz [23], which are usually removed by high-pass filtering. Manchester coding, by mitigating the low-frequency components of the data signal, allows to limits the distortions induced by such filtering. However, since two bit periods are needed to transmit one information bit, the ratio between the data rate R_b and the clock rate f_c will be 1/2.

Table 1. OOK and PAM-4 modulation with Manchester coding

OOK		PAM-4	
Input bit	**Output power**	**Input bits**	**Output power**
0	$\{0, P_t\}$	00	$\{0, P_t\}$
		01	$\{1/3P_t, 2/3P_t\}$
1	$\{P_t, 0\}$	11	$\{2/3P_t, 1/3P_t\}$
		10	$\{P_t, 0\}$

PAM-4 is an extension of OOK, where two intermediate levels are added between the fully off and on states. Consequently, the information bits can be encoded by sequences of two into a single symbol of power 0, $1/3P_t$, $2/3P_t$ or P_t and duration $1/f_c$: PAM-4 allows to double the data rate while keeping the same bandwidth requirements as OOK. However, as in OOK, the spectrum of a PAM-4 encoded signal contains a main lobe centered on the null frequency, which means ambient light removal by filtering may generate signal distortions. Manchester coding will thus be added to PAM-4, as outlined by Table 1, so that the ratio R_b/f_c is 1.

2.2. Optical GSSK

GSSK is a specific form of spatial modulation where one or several transmitters are active at the same time instant. If two transmitters are used, then four different states are possible: both transmitters on or off, or only one transmitter on with the other off. Information bits can thus be encoded by sequences of two, which means that GSSK, as PAM-4, doubles the data rate while keeping the same bandwidth requirements as OOK. Since each transmitter acts as an OOK source, Manchester coding is once again used, which gives the coding Table 2 and limits the ratio R_b/f_c to 1.

Unlike OOK or PAM-4, the number of transmitters and their positions have a direct impact on the shape of the light signal collected by the receiver. If two transmitters are used, we can expect four different amplitudes, just like with PAM-4. However, if the intermediate levels remain fixed with PAM-4, we can understand intuitively that in GSSK, they will vary according to the portion of light collected from one LED or the other. This behavior will have an impact on the decoding procedure, as we will see in Section IV.

Table 2. GSSK modulation with two transmitters and Manchester coding

Input bits	Output power (LED 1)	Output power (LED 2)
00	$\{0, P_t\}$	$\{0, P_t\}$
01	$\{0, P_t\}$	$\{P_t, 0\}$
11	$\{P_t, 0\}$	$\{0, P_t\}$
10	$\{P_t, 0\}$	$\{P_t, 0\}$

3. VLC system and experimental set-up

Before exploring the performances of the three modulations just described for automotive applications, the experimental set-up has to be detailed. In this section, the VLC transmitter is fully presented, from the headlamp characterization to the data packets structure. Then, the different receiving steps are specified, from the signal reception to its decoding.

3.1. VLC transmitter

During the experiments, data are transmitted by packets of specific format. Each packet is indeed composed of 400 information bits encoded with the desired modulation. Note that such a length is, according to the USDOT, adapted to the transmission of the most crucial data in automotive applications [5]. The data bits are preceded by a specific header which, in our case, is limited to four consecutive high levels of power P_t. Since this sequence is strictly forbidden by Manchester coding, it can only correspond to the beginning of a packet. However, note that more complex header could be used, as we will see in Section 4.4.

Each bit of a packet is sent at a clock rate f_c by two COTS white LED headlamps, which can be characterized by the curves given in Figs. 1 and 2. Figure 1(a) represents the evolution, with the forward current, of the maximum illuminance at 50 cm output by one headlamp. It may be noted that, although the nominal current of our headlamps in low-beam operation is 1 A, the VLC system will be here limited to 600 mA, corresponding to a maximum illuminance at 50 cm of around 67 klux. It should also be observed that the output illuminance does not increase linearly with the forward current.

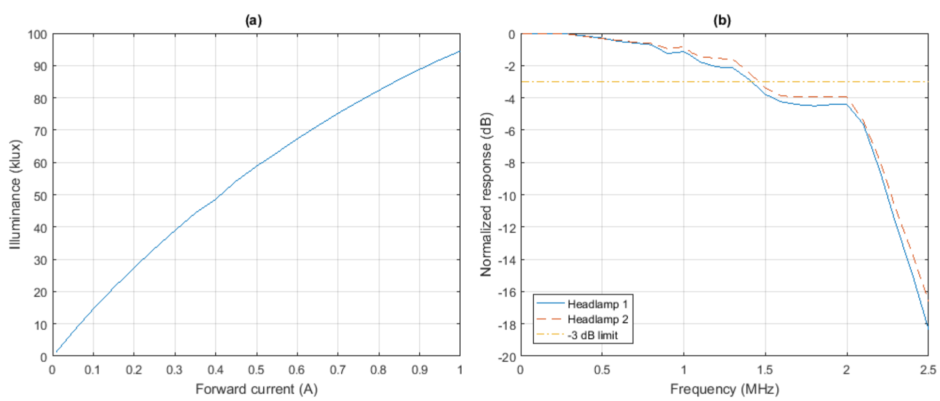

Fig. 1. (a) Evolution of the maximum illuminance at 50 cm of both headlamps with the forward current and (b) their frequency responses.

This first optical characterization is extended in Fig. 2, by representing the spatial light distribution obtained by measuring, with a luxmeter, on a vertical plane at 4.5 m from a headlamp driven at 600 mA, the different illuminances by step of 10 cm horizontally and 5 cm vertically. Note that both headlamps have the same beam pattern so they can be used independently as right or left transmitter. In addition, it can be deduced that the semi-angle at half illuminance, which is the angle at which the illuminance is half its maximum value, is in both cases 3° when measured in the horizontal plane of vertical position 0. This shows that our headlamps are actually rather directive. Finally, Fig. 1(b) shows the normalized frequency responses of both headlamps, measured by transmitting a sine wave of varying frequency and mean current 300 mA and observing the amplitude of the resulting light signal with a Thorlabs PDA8A photoreceiver having a 50 MHz bandwidth. These curves allow to determine that the 3 dB bandwidth of our LED transmitters is between 1.4 and 1.5 MHz.

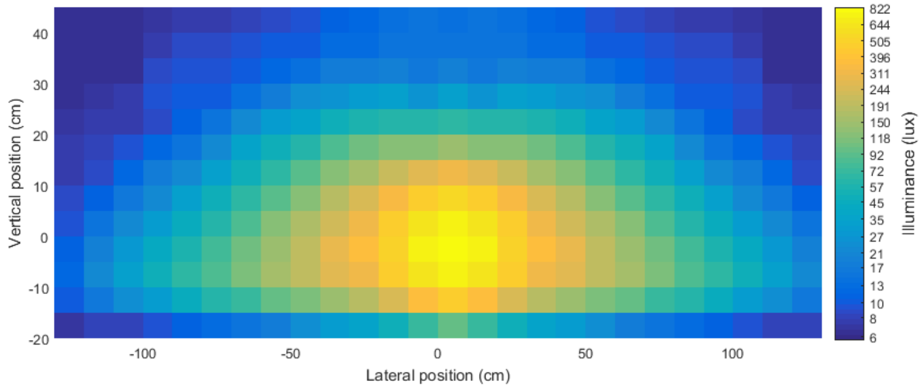

Fig. 2. Spatial distribution of the illuminance of a headlamp when projecting on a vertical plane at 4.5 m. The point of origin is the point of maximum illuminance.

In practice, the data frames are obtained by generating random bits with MATLAB that are then encoded and added to the predefined header. The resulting data signal, containing eventually 10^6 information bits, is then uploaded to a Tecktronix AFG3020 waveform generator used to control the drivers of both headlamps. Since OOK, PAM-4 and GSSK are all intensity modulations, these drivers simply need to control, at a fixed clock rate f_c, the optical power emitted by the LED depending on the symbol to transmit. Therefore, they are simple metal oxide semiconductor field effect transistors (MOSFET) which gate voltage, produced by the waveform generator, controls the current flowing through the corresponding LED.

3.2. VLC receiver

At the other end of the VLC system is the receiver, which general architecture is represented on Fig. 3.

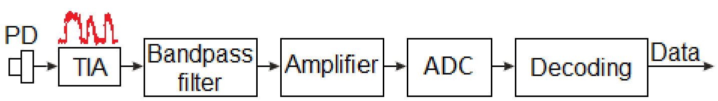

Fig. 3. The VLC receiver, composed of a photodiode (PD) and a trans-impedance amplifier (TIA) followed by a filter, an amplifier and an analog-to-digital converter (ADC).

The light signals transmitted by both headlamps are first collected and converted into a photocurrent using a 40 MHz bandwidth Hamamatsu S3590 PD, and then turned into an amplified voltage signal by a transimpedance amplifier (TIA). These two first stages form a custom-made front-end of voltage gain 46.6 dB and 3 dB bandwidth 1.5 MHz. Then, the resulting electric signal is filtered using a simple first-order bandpass filter, of low-pass cutoff frequency equal to 1.5 MHz and high-pass cutoff frequency of 1 kHz. These filters allow to limit the impact of the other light sources while removing some of the channel noise. The filtered signal is then amplified using a variable gain amplifier before sampling with an analog-to-digital converter (ADC). After sampling, demodulation and decoding is performed using a digital platform.

The decoding algorithm is based on comparison and samples counting. Each sample is compared to one or several thresholds, depending on the modulation used, in order to classify it in an amplitude zone. At the same time, the number of consecutive samples belonging to the same zone is counted, as illustrated by Fig. 4 with OOK and PAM-4. Figure 4(a) shows a portion of OOK signal after reception and processing. The black horizontal line highlights the two decoding zones, by defining the threshold over which the samples correspond to a 1 and below which they represent a 0. Similarly, Fig. 4(b) shows a PAM-4 signal with, this time, the four corresponding decoding zones. In both cases, the distribution of the number of consecutive samples belonging to the same zone is as represented on Fig. 4(c). It is clearly divided in two peaks. The left peak corresponds to the occurrence of a single light level whereas the right peak denotes the occurrence of two consecutive identical light levels, the maximum allowed by Manchester coding. Since these two peaks are clearly distinguishable, the count values can simply be compared to a fixed threshold to complete the decoding [10, 12]. Note that in the case of PAM-4, if the signal amplitude varies, then the decoding thresholds for the intermediate levels will have to be continuously adjusted. However, if the peak-to-peak amplitude is kept constant for all V2V distances, using for instance an adjustable gain, there is no need to modify these thresholds.

Here, the gain is selected by hand, through a potentiometer, so that the peak-to-peak amplitude stays at ±1 V. The resulting signal is then sampled at a rate $12.5 f_c$ using a Tecktronix MDO3054 oscilloscope. The samples obtained are finally decoded offline on MATLAB, with the sample count method.

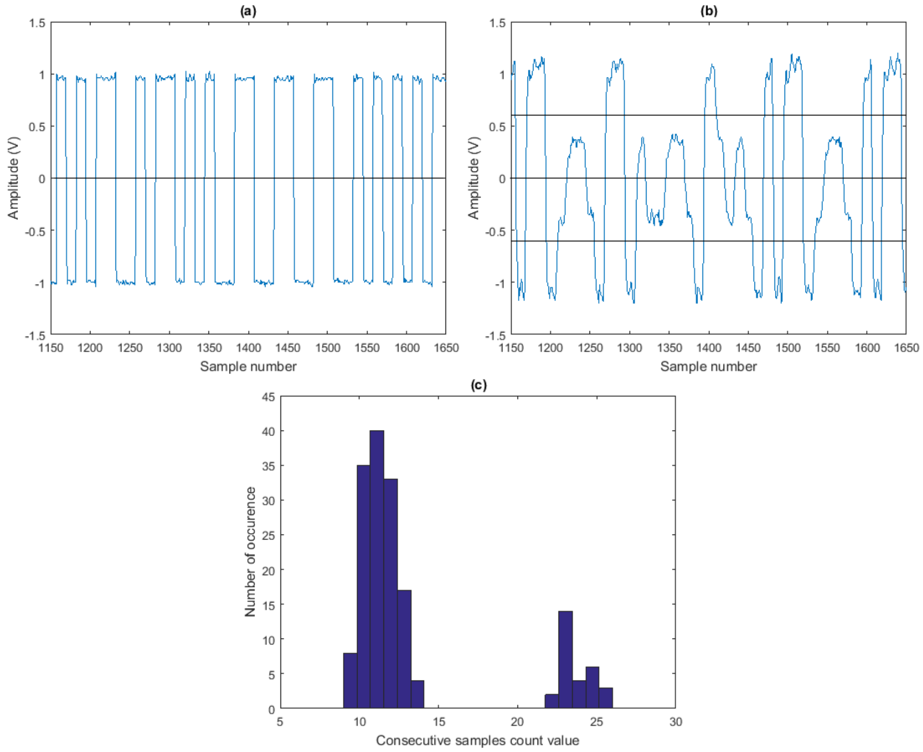

Fig. 4. Examples of (a) OOK and (b) PAM-4 data signals, with their respective decoding zones defined by the black horizontal lines, whereas (c) is the distribution of the resulting consecutive samples count values in the case of PAM-4, with a sampling rate of $12.5 f_c$.

3.3. Experimental set-up

These core bricks are integrated in a more general set-up to simulate a platoon of two vehicles and evaluate the performances of the different modulations in straight line and curve configurations. Both vehicles are represented with mobile tables. On the FV side, the two headlamps are fixed with an inter-distance of 1.2 m and they emit toward the same direction. On the LV side, two distinct VLC receivers, spaced by 1.2 m, are directed toward the headlamps and placed in their horizontal plane of maximum illuminance. In addition, both the emitters and receivers are at 80 cm above ground.

Figure 5 shows two consecutive vehicles in a platoon, separated by a distance d in a curve of center C and fixed radius R. From this geometry, we can define the angle α that completely defines with d the relative position of both vehicles. This angle is linked with R and d through the relation:

$$\alpha = \sin^{-1} \frac{d}{2R}. \tag{1}$$

By playing on these two parameters, we can test several configurations. In particular, if $\alpha = 0$ and d varies, then we are in a straight line configuration. If instead d remains fixed and α varies, then we are in the configuration of a curve with a changing radius.

Note that all the experiments were carried out in a 30 m building corridor, with a 100 Hz ambient lighting giving a mean illuminance of 150 lux. Therefore, the perturbations induced are not as massive as they would be in real daytime outdoor applications. These optimal conditions allow us to isolate the behavior of the system according to the modulation only.

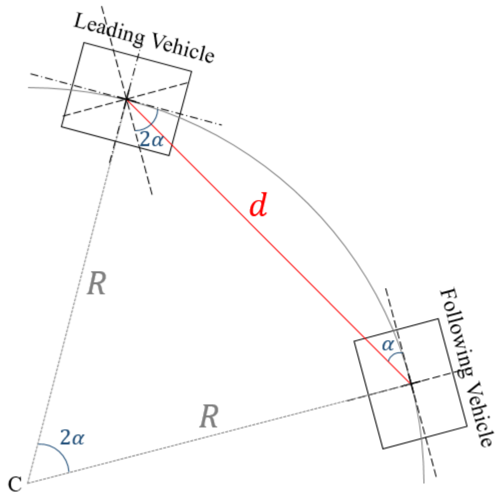

Fig. 5. Two-vehicles platoon of inter-distance d, in a curve of center C and radius R and fully defined by the angle α.

4. Modulations comparison

4.1. Straight line configuration (α = 0)

In these first tests, both vehicles are aligned in a straight line ($\alpha = 0$). A full transmission cycle of 10^6 information bits is performed for each modulation every 5 m, from 5 m to 30 m, with a clock frequency f_c of 200 kHz. The data rates reached are thus 100 kbps with OOK and 200 kbps with PAM-4 and GSSK.

Figures 4(a) and 4(b) show the signals sampled by one of the receiver while the V2V distance is 30 m, when OOK and PAM-4 are used respectively. As we can see, the different light levels in both cases can be clearly identified, showing that the signal-to-noise ratio (SNR), even at large distance, remains good. By using a threshold at 0 V for OOK, and three thresholds at 0 V and ±0.75 V for PAM-4, the data can be decoded without any errors over 10^6 bits. We can conclude that, up to 30 m, the BER with these two modulations is below 10^{-6}. In addition, note that although two receivers are used, only one receiver is needed to decode the data. Consequently, the second sensor can be used for redundancy.

In the case of GSSK, similar BER performances are observed, although the behavior of this modulation is rather different. According to Table 2, each receiver will detect either no light, or the light of only one transmitter, or the light of both transmitters. Depending on the emitter/receiver alignment, the corresponding light levels detected will vary. Figure 6 illustrates this behavior by representing, in the straight line configuration ($\alpha = 0$), the signals sampled by both receivers when the V2V distance is (a) 5 m, (b) 10 m and (c) 30 m.

First, at 5 m, Fig. 6(a) shows that both receivers output only two distinguishable levels. The signal amplitude output by the left receiver when the left headlamp is on is more or less the same as when both headlamps are on, while the converse is true for the right receiver. In other words, the additional light power collected by a receiver from the opposite transmitter is negligible compared to the light power collected from the adjacent transmitter. This observation is in complete accordance with the beam pattern given in Fig. 6(d), which shows the illuminance evolution with the lateral distance at the receivers level, obtained by projecting the beam pattern measured in Fig. 2 using the free-space optical propagation model [24]. It appears clearly that both the right and left receivers, positioned respectively at 0.6 m and -0.6 m, collect a total amount of light mainly produced by the right and left headlamps respectively.

However, the opposite transmitter has an growing influence as the V2V distance increases. Figure 6(b) shows that at 10 m, the signals sampled by both receivers contain a first intermediate level at -0.6 V, reached when only the opposite transmitter is active, and a second intermediate level at 0.6 V, reached when only the adjacent transmitter is active. The same observation can be made from Fig. 6(c), where the distance is 30 m, except that the intermediate levels are now at ±0.2 V. Figures 6(e) and 6(f) represent the illuminance distributions at the receivers level when the V2V distance is respectively 10 m and 30 m. They shows that, at 10 m, the adjacent headlamp contributes to around 80% of the light collected by the corresponding receiver while the remaining 20% come from the opposite headlamp. At 30 m, this balance is reduced to 60%/40%. Note that these percentages are, when converted into voltages, quite close to the ±0.6 V and ±0.2 V levels, which shows the validity of the projection used to obtain these illuminance distributions.

Although the intermediate levels may vary, both receivers only output a positive voltage when the adjacent LED, at

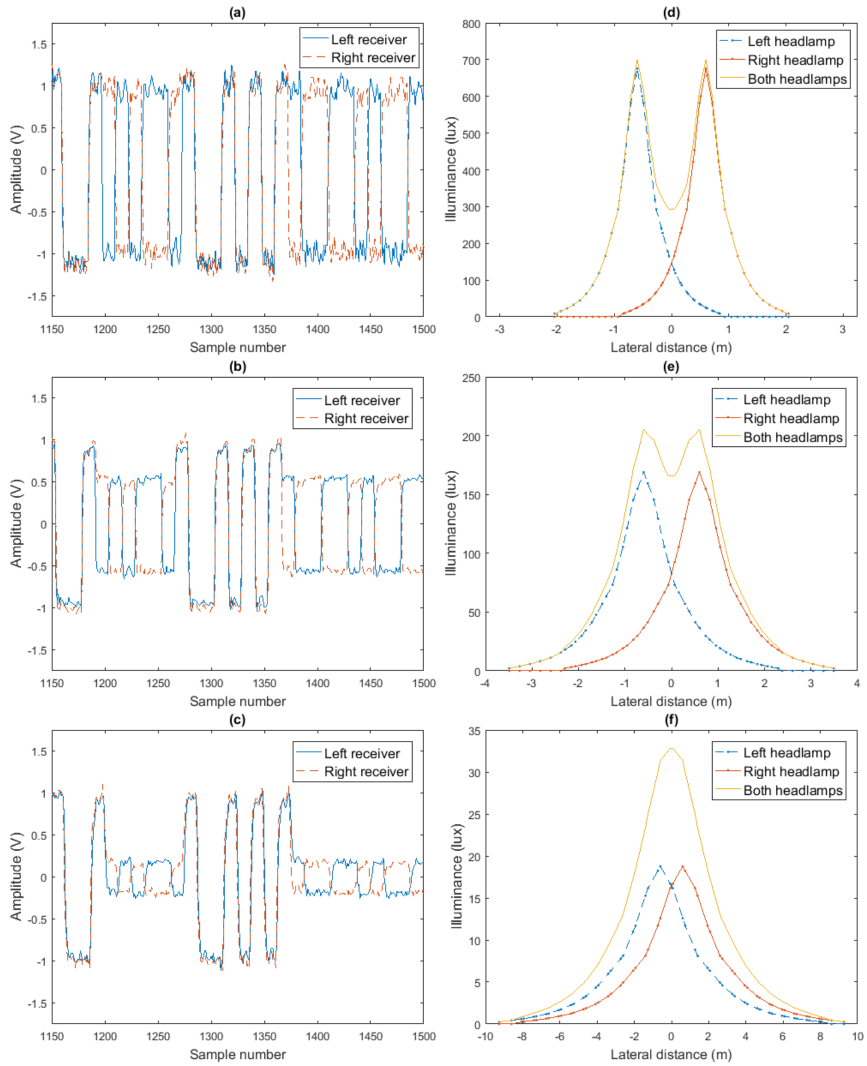

Fig. 6. Left column: GSSK signals sampled by the left receiver (blue line) and the right receiver (orange dashes) when the V2V distance is (a) 5 m, (b) 10m and (c) 30 m. Right column: Lateral evolution, at the receivers level, of the illuminance produced by the left headlamp (blue dotted dashes), the right headlamp (red dotted plain line) and both headlamps (orange line) when the V2V distance is (d) 5 m, (e) 10 m and (f) 30 m.

least, is on. Consequently, a simple threshold at 0 V followed by pulse width decoding allows each receiver to detect the current state of the corresponding LED. Then, if the ADC of both receivers are driven by the same master clock, we can obtain synchronous samples and combine them to determine the current state of both headlamps, or equivalently the symbol transmitted. The use of two receivers is thus crucial, since it avoids the need to determine intermediate thresholds as in PAM-4. With this method, all the bits were properly received, which means that, up to 30 m, the BER of our system with GSSK remains below 10^{-6}.

However, we can guess that from a certain distance, the contribution of both headlamps to the signals received will be almost equal, which means that the intermediate levels will be merged and that proper decoding will not be possible anymore. For example, at 50 m, the adjacent and opposite headlamps represent respectively 55% and 45% of the optical signal collected, so they are rather complex to distinguish, especially in a high noise environment. Therefore, the longitudinal range of use of GSSK is limited to several tens of meters, even though this range is large enough for platooning applications, especially in cruise mode.

4.2. Curve configuration (d = 10 m)

We are now considering the same experimental protocol while the vehicles are separated by 10 m and driving in a left curve of radius R. As illustrated by Fig. 5, the headlamps and receivers will not be aligned anymore. The left receiver will mainly collect the light produced by the left headlamp, whereas the right receiver will still receive contributions from both transmitters. This behavior will then be amplified as the curve radius decreases. Here, several radius have been tested down to a minimum value of 100 m. This value can be considered as an extreme limit for highway platooning applications.

With OOK and PAM-4, both receivers detect the same data signal, even though before amplification, the peak-to-peak amplitude of the left signal is lower than the right one. As in the straight line configuration, the data can thus be decoded independently by both receivers. Using the same decoding process as previously, we found no errors in the retrieved bits, which means that the BER remains below 10^{-6} even in curve configurations.

In the case of GSSK, the relative position of both vehicles has a different impact on the signals sampled than in the straight line configuration. Figure 7 shows the signals sampled by both receivers in the extreme case of a radius $R = 100$ m. If the intermediate levels are still clearly visible on the left signal, they are rather close on the right one. As mentioned previously, this is due to the fact that the right receiver will collect light from both transmitters whereas the left one will mainly detect the left headlamp. However, the intermediate levels are still in both cases enough spaced to use the same decoding technique as previously. In the end, there are no errors detected so the BER is also below 10^{-6} with GSSK in curve configurations.

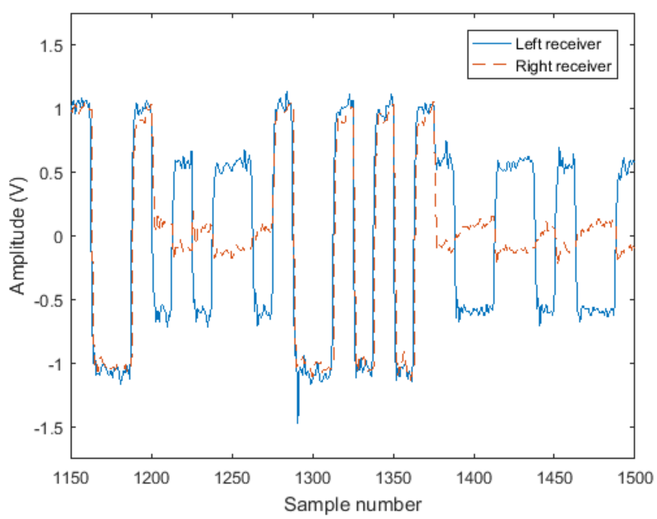

Fig. 7. Example of GSSK data signals sampled by the left receiver (blue line) and the right receiver (orange dashes) when the FV/LV distance is $d = 10$ m and the radius of the curve is $R = 100$ m.

4.3. Behavior with larger clock rates

In order to reach megabits per second data transmission with either OOK, PAM-4 or GSSK, the clock rate f_c has now to be increased. However, since the 3 dB bandwidth of both headlamps is, as shown on Fig. 2(b), around 1.5 MHz, f_c cannot be brought up to more than a few megahertz. Here, a clock rate of 2 MHz is considered. In such a case, we must expect signal distortions that may have an impact on the transmission performances. In order to isolate this impact, the custom-made receivers used so far have been replaced by Thorlabs PDA8A of bandwidth 50 MHz, directly connected to the sampling oscilloscope, and placed in a straight line configuration with $d = 10$ m. The rest of the experimental protocol remains unchanged.

Figure 8 shows the data signals received with each modulation and for various clock frequencies. Figure 8(a) shows that, when $f_c = 2$ MHz, despite pulse distortions, both OOK levels can be clearly identified, as well as their width. The sample count histogram obtained in this case shows indeed two clear groups, as in Fig. 4(c), and the decoded data do not contain any errors over 10^6 bits. Our headlamps can thus be used with OOK to provide a 1 Mbps link with a BER below 10^{-6}.

This is not the case with PAM-4. Figure 8(b) shows the same portion of received signal as f_c is increased from 200 kHz to 2 MHz. At 200 kHz, the four different levels, and especially the intermediate levels, appear clearly. However, at 500 kHz, they are already slightly masked by the limited rising and falling times of the headlamps as shown, for instance, at sample number 650. Then, when $f_c = 1$ MHz, the headlamps are too slow to properly transmit every levels like, for example, at sample number 725. Logically, this behavior gets worse as the clock rate increases to 2 MHz. It was actually found that the BER remains below 10^{-6} only up to $f_c = 400$ kHz.

Finally, Fig. 8(c) shows that with GSSK, the intermediate levels at 2 MHz are not always as constant as at 200 kHz. However, both the left and right signals can be decoded as OOK signals without ambiguity. Here, GSSK takes advantage of the fact that each headlamp is actually an OOK source for which the distortions are as limited as shown on Fig. 8(a). Consequently, the intermediate levels do not suffer from the bandwidth limitations as much as PAM-4 since they correspond to one fully on transmitter. After decoding each source and combining the results, there were once again no errors over 10^6 bits. In other words, a 2 Mbps link of BER below 10^{-6} is possible with GSSK.

4.4. Discussion on the results

In the light of the different results obtained in the previous sections, a radar chart based on three characteristics - the data rate, the simplicity and the mobility for a BER below 10^{-6} - can be built, as shown on Fig. 9. PAM-4 appears as the less interesting modulation. Since both headlamps transmit the same signal, the data may be received as long as one of the photoreceiver is in the field of emission. The beam shape of the headlamps, given on Fig. 3, then covers an area large enough to ensure proper reception of the light signal in classical highway platooning configuration. Therefore, the mobility of PAM-4 can be seen as good. However, the limited bandwidth and non-linearity of white LED headlamps prevents from increasing the data rate. In addition, PAM-4 requires accurate current driving of the LED to respect the intermediate light levels and the decoding process in based on multiple thresholds, which means this modulation may be complex to implement, especially when compared to OOK or GSSK.

The tradeoff is thus between OOK and GSSK. On the one hand, OOK exhibits similar mobility properties as PAM-4 because, once again, both headlamps transmit the same data signal. In addition, this modulation is very simple to implement. The transmit LED simply needs to be turned on and off, whereas a single receiver with zero-crossing detection is sufficient. Finally, despite the LED bandwidth limitations, the data rate can reach 1 Mbps.

On the other hand, GSSK can double the data rate of OOK and yet ensure a BER below 10^{-6}. However, these performances would probably not be achieved with a single receiver. The use of two receivers properly spaced allows indeed to detect independently the states of each LED and then combine them to decode the data. Consequently, the receiver design with GSSK is a little more complex than with OOK. However, it must be pointed out that with a single receiver, GSSK decoding would imply varying intermediate thresholds, which would eventually be even more difficult. In such a case, as proposed in [22], channel information bits can be sent in each packet header so that the receivers can estimate the amplitude of the different light levels and then set the intermediate thresholds. Finally, GSSK resisted to all the configurations evaluated so we can consider it provides a good mobility for highway platooning configurations. However, one could wonder what would happen beyond the extreme cases tested here. In the straight line configuration, we know that from a certain V2V distance, the GSSK intermediate levels are merged. In such a case, GSSK is simply unusable. In curve configurations now, if the radius R goes below 100 m, we can expect the right signal to have merged intermediate levels. However, the left signal may exhibits levels as clear as on Fig. 7 so that it would still be possible to decode the data with this receiver only.

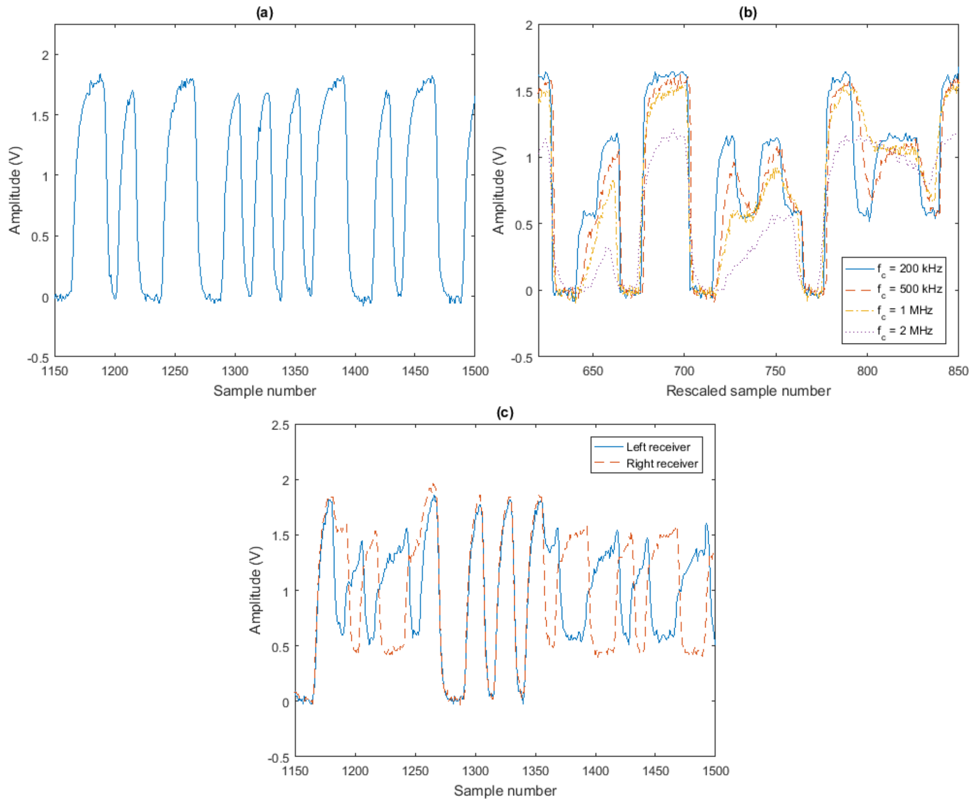

Fig. 8. Example of (a) OOK data signal with f_c = 2 MHz, (b) PAM-4 data signals with f_c = 200 kHz (blue line), f_c = 500 kHz (red dashes), f_c = 1 MHz (yellow dots-dashes) and f_c = 2 MHz (purple dots) and (c) GSSK data signals of the left (blue line) and right (red dashed line) receivers, with f_c = 2 MHz. In (b), signals are time scaled to ease comparison.

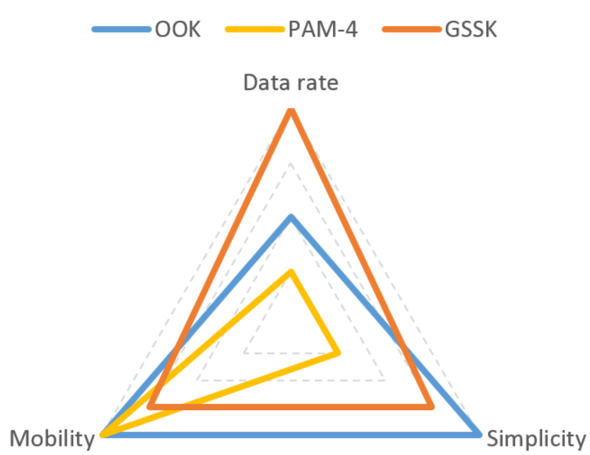

Fig. 9. Comparison of the characteristics of OOK, PAM-4 and GSSK according to their data rate, simplicity and mobility, for a BER below 10^{-6}, in highway platooning configurations.

5. Conclusions and future works

Three pulse modulations are investigated in this work for VLC vehicular communication in highway platooning configurations: OOK, PAM-4 and GSSK. A prototype based on two COTS white LED headlamps with their proper drivers for data transmission and custom-made or COTS photoreceivers for data reception, is detailed. Tests in straight lines for V2V distances up to 30 m and in curves of minimum radius 100 m and V2V distance 10 m are carried out. These experiments show that, in a highway platooning perspective, OOK and GSSK are the most interesting modulations. OOK is indeed reliable and simple to implement. A 1 Mbps link of BER below 10^{-6} is demonstrated. However, this data rate is brought up to 2 Mbps, with an equivalent BER, when using GSSK. These performances are especially made possible by the use of two spatially distinct receivers. In GSSK, the LED acts indeed as OOK sources. Each receiver can thus decode one specific source and the results can then be combined to recover the transmitted symbol. However, the tests carried out here are limited to indoor conditions, or equivalently outdoor night conditions. Consequently, the next step of this work will consist in embedding a complete VLC prototype supporting OOK and GSSK on vehicles and testing it in real daytime conditions.

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